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LOCAL HEAT TRANSFER FOR WATER IN ENTRANCE REGIONS OF TUBES WITH TAPERED FLOW AREAS AND NONUNIFORM HEAT FLUXES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Local convective heat-transfer coefficients for water flowing through electrically heated circular tubes with axially varying heat fluxes and flow areas were investigated. Data were obtained in the turbulent flow regime with local Reynolds numbers from 8000 to 50 000 over a Prandtl number range of 1.6 to 4.5. Measurements of mass flow rate, heat flux, water bulk temperatures at tube inlet and outlet, and axial temperature distribution for each run were made and are presented in tabular form. Plots of local to fully developed Nusselt number ratio as a function of heated length-to-diameter ratio are presented. These data are compared with calculated values of the local to fully developed Nusselt number ratios based on a previously reported correlation of entrance effects with tubes of constant flow area and uniform heat flux. The calculated Nusselt number ratios generally approximated the present experimental results.

INTRODUCTION

A knowledge of the variation in local heat-transfer coefficients for liquids flowing in tubes of nonuniform cross-sectional flow area and nonuniform heat flux is directly applicable in the design of fluid-cooling channels for rocket nozzles. Tube-and-shell type heat exchangers and boilers could also conceivably benefit by the use of nonuniform cross-sectional area tubes.

Experimental heat-transfer data are presented in reference 1 for water flowing in constant-flow-area, uniform-heat-flux tubes that had several short unheated lengths preceding the heated portions. Reference 1 also contains a review of other investigations of heat-transfer coefficients in the entrance regions of tubes. However, limited experimental data have been published on the variation with length of local turbulent heat-transfer coefficient of liquids in entrance regions of heated tubes with square-edged

inlets. Especially lacking are data for tubes with nonuniform cross-sectional flow area, nonuniform heat flux, or both. The investigation described herein was initiated to obtain such data.

Two test sections were used in the present study. The first consisted of a modified section of stainless steel tubing used for cooling an experimental rocket engine, and the second was a chemically milled tapered wall Inconel tube. The first test section had a tapered cross-sectional flow area with a nonuniform heat flux. The flow area increased in the direction of decreasing heat flux. The total length of this test section was $53\frac{1}{8}$ inches (135 cm). The inside diameter varied linearly from 0.380 to 0.844 inch (9.6 to 21.4 mm). The heat flux ratio over the entire length was approximately 16 to 1 because of the tube and wall thickness taper.

The second test section had a constant internal flow area with a diameter of 0.431 inch (10.9 mm) and a tapered wall thickness. The total length of this test section was 43 inches (109.2 cm). The heat flux ratio over the entire length was 2 to 1. The two test sections were reversible and were tested in both directions of flow.

The ranges of conditions investigated in this report were as follows:

Mass flow rate, lb/hr (kg/sec)	370 to 2000 (0.047 to 0.252)
Heat flux, $(Btu/hr)/ft^2 (W/m^2)$	0 to 6.5×10^5 (0 to 2.05×10^6)
Local bulk temperature, $^{\circ}F$ ($^{\circ}K$)	100 to 250 (310 to 395)
Reynolds number	8000 to 50 000
Prandtl number	1.6 to 4.5

APPARATUS

The experimental data were obtained with the test equipment described in detail in reference 2 and shown schematically in figure 1. The flow system is a closed loop in which the water is recirculated by a gear pump. The major components of the loop consist of a resistance-heated stainless steel preheater, a resistance-heated test section, and a water-cooled heat exchanger. The loop is pressurized at a surge tank which is connected to the loop at the pump inlet. The power for heating the test section and the preheater is supplied by two separate saturable core reactors and transformers.

Two test sections were studied in this investigation. The first section, shown schematically in figure 2, was obtained from tubing used to cool an experimental rocket engine. It was fabricated of type 304 stainless steel. The total length of the test section was $53\frac{1}{8}$ inches (135 cm), of which $52\frac{1}{4}$ inches (132.7 cm) was considered as the heated length. The inside diameter varied linearly from 0.380 to 0.844 inch (9.6 to 21.4 mm). The outside diameter varied linearly from 0.410 to 0.940 inch (10.4 to 23.9 mm). The

cross-sectional flow area ratio and the heat flux ratio for the entire length of the test section were approximately 1 to 5 and 16 to 1, respectively.

The second test section had a constant internal flow area with a tapered wall thickness and was fabricated from 1/2-inch (12.7 mm) diameter Inconel tubing. The inside diameter was 0.431 inch (10.9 mm). The outside diameter was chemically milled to vary linearly from 0.464 to 0.500 inch (11.8 to 12.7 mm). The heat flux ratio over the entire length of this section was 2 to 1. The total heated length was 43 inches (109.2 cm). Copper bus bars were attached to both ends of the test sections for applying electrical power.

The system flow rates were measured by a turbine-type flowmeter. The flowmeter output was read from a frequency converter and checked with a counter. The system pressure was measured by a bourdon tube gage connected at the pump inlet. Chromel-Alumel thermocouples were spotwelded to the outer wall of the test sections at the same circumferential position for all axial temperature measurements. Inlet and outlet bulk temperatures were measured by thermocouples in the liquid stream at the inlet and outlet plenums. All the temperatures were recorded on self-balancing potentiometers. The ac power to the test section was measured by a dynamometer-type wattmeter. The voltage drop across the test section was measured by a vacuum tube voltmeter.

PROCEDURE

Each day before data were taken, water was circulated and boiled in the test section. Noncondensable gases were vented from the system through a line connected to the high point of the loop. Dissolved gas content was maintained at less than 3 ppm by weight based on the average molecular weight of air.

In order to check the thermocouples, runs were made in which heat was applied to the preheater only. Since the heat losses from the test section to the surrounding environment were small, the tube outer wall temperatures could be checked for consistency against the water bulk temperatures at the inlet and outlet plenums. This was done over the range of bulk temperatures encountered by adjusting the preheater power. The temperature recording instruments were calibrated before and after each series of runs.

The conditions for each run were established by adjusting the power to the preheater and test section, thus setting the inlet and outlet bulk temperatures, for preselected values of flow rate. When the inlet and outlet bulk temperatures became constant with time, the data for that run were taken. The system surge tank pressure was maintained at 120 psig (828 kN/m^2).

DATA REDUCTION

The current through the test section was computed from the wattmeter and corresponding voltmeter readings. The local heat flux at the inside wall of the test section was calculated from the following equation:

$$q = 3.413 \frac{I^2 \alpha}{\pi D_i A_w}, \qquad \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)}$$

or

$$q = \frac{I^2 \alpha}{\pi D_i A_w}, \qquad \frac{\text{W}}{\text{m}^2}$$

where

I current through test section, A

α electrical resistivity, ohm-ft (ohm-m)

D_i local inside diameter, ft (m)

A_w local wall cross-sectional area, ft^2 (m^2)

The total resistance of the first test section was measured at 70° and 230° F (294° and 383° K). The values obtained were 0.0299 ohm and 0.0333 ohm, respectively. These values of total resistance were substituted in the electrical resistivity equation

$$\alpha = \frac{R}{\int \frac{dx}{A_w}}$$

where R is total test section resistance in ohms and dx is incremental test section length in feet (m), to obtain the resistivity equation as a function of temperature

$$\alpha = 2.28\times10^{-6} + 1.71\times10^{-9}\ T \text{ ohm-ft}$$

where T is temperature, $^{\circ}$F. A similar expression was determined for the second test section. When the local heat flux was calculated, the local resistivity based on the local outside wall temperature was used.

The local outside wall temperatures were obtained from the axially located thermocouples by means of the curve of calibrated electromotive force against temperature for Chromel-Alumel thermocouples. The inside wall temperature was computed as in reference 2, considering internal heat generation and no axial heat flow. The thermal conductivity of the stainless steel test section was obtained from reference 3, and that for Inconel from reference 2.

The values of local Nusselt, Reynolds, and Prandtl numbers were computed on the basis of the physical properties of water evaluated at the local bulk temperatures. The water local bulk temperatures were obtained by a heat balance. The physical properties of water were obtained from reference 4.

The local fully developed Nusselt number to which measured values were ratioed was computed from the local values of Reynolds and Prandtl numbers by the following relation obtained from reference 1 as an approximation for Prandtl numbers from 1.5 to 8:

$$Nu_{fd} = 0.023(Re)^{0.8}(Pr)^{0.47}$$

where

Nu_{fd} local fully developed Nusselt number

Re local Reynolds number

Pr local Prandtl number

The calculated local Nusselt number ratio of reference 1 with which the experimental ratios were compared was obtained by the following equation, which was for the case of constant flow area and uniform heat flux:

$$\frac{Nu}{Nu_{fd}} = 1 + \frac{2.3}{0.5\, z^2 + z + z^{1/4}} \qquad Re \geq 8000$$

where

$$z = \frac{\sqrt{xy}}{D_i Pr^{0.4}} \sqrt{\frac{1}{1 + 0.01\, y/D_i Pr^{0.4}}}$$

z distance and physical properties parameter

x heated length to local point of test section (see fig. 2)

y total length to local point of test section (see fig. 2)

RESULTS AND DISCUSSION

The experimental data for the tapered-flow-area, nonuniform-heat-flux test section are presented in table I. The data for the constant-flow-area, tapered-heat-flux test section are presented in table II. These tables contain the local heat flux and outside wall temperatures, as well as calculated inside wall and bulk temperatures, and local Prandtl, Reynolds, and Nusselt numbers.

A plot of Nu/Nu_{fd} against the ratio of length from the start of heating to local diameter for the tapered-cross-sectional-flow-area test section is presented in figure 3. The lower curve represents the experimental data for the diverging flow area case and the upper curve for the converging flow area. Also presented are the calculated curves for both cases. These calculated curves were obtained using the distance and physical property parameter z of reference 1. The curves shown are faired through the calculated points for all the data runs in their respective directions of flow. It can be seen from the data that the converging flow (and increasing flux) case gives a slightly higher Nusselt number ratio than the diverging flow case at the same x/D ratio for ratios less than 10. This trend is shown by the calculated results, to a smaller degree. In both cases the experimental Nusselt number ratio exceeds the calculated.

The Nusselt number ratio is plotted against the length-to-diameter ratio for the constant-flow-area, tapered-flux test section in figure 4. Figure 4(a) presents the data for decreasing heat flux in the direction of flow and figure 4(b) the data for increasing heat flux. The respective faired calculated curves using the z parameter correlation. are also plotted. Although a small effect of Prandtl number on the Nusselt number ratio does exist, it was not presented because of the limited data taken and is not of magnitude to significantly affect the results presented herein. The experimental results can be approximated in both cases by the z parameter correlation

SUMMARY OF RESULTS

The present investigation has shown that the distance and physical properties parameter of NASA TN D-3098 can be used to approximate the local Nusselt number ratio near the entrances of tubes with tapered flow areas and nonuniform heat fluxes, over the range of conditions tested.

The ratio of local to fully developed Nusselt number is slightly greater for converging flow area and increasing heat flux than for the opposite case at the same ratio of heated distance to local diameter near the inlet of the test section studied.

For the range of conditions tested the effect of flow direction on heat transfer was slightly more pronounced for the nonuniform-flow-area, nonuniform-heat-flux test section than for the nonuniform-heat-flux, constant-flow-area test section.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 3, 1968.
120-27-02-03-22

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TABLE I. - EXPERIMENTAL DATA FOR TAPERED-FLOW-AREA,

NONUNIFORM-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	Btu/(ft^2)(hr)	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 101: Increasing heat flux, converging flow area; mass flow rate, 2000 lb/hr (0.252 kg/sec); power to test section, 25 800 W; test section voltage, 29.6 V; inlet bulk temperature, 106 ^oF (314 ^oK); outlet bulk temperature, 150 ^oF (339 ^oK)													
0.25	0.64	30.70×10^3	9.68×10^3	125	325	118	321	106	314	4.20	23.71×10^3	486	143
.50	1.27	30.70	9.68	125	325	118	321	106	314	4.20	23.74	485	143
.75	1.91	30.70	9.68	127	326	120	322	106	314	4.20	23.81	415	143
1.00	2.54	30.75	9.69	129	327	122	323	107	315	4.15	24.20	386	144
1.50	3.81	31.55	9.95	131	328	126	325	107	315	4.15	24.30	311	145
2.00	5.08	32.32	10.19	135	330	128	327	107	315	4.15	24.43	287	145
4.25	10.80	35.54	11.20	144	335	137	332	108	315	4.11	25.38	223	149
8.25	20.96	41.90	13.21	157	343	149	338	109	316	4.08	26.70	182	155
12.25	31.12	50.70	15.98	165	347	156	342	111	317	3.99	28.76	186	163
16.25	41.28	59.20	18.66	172	351	162	345	112	318	3.94	30.42	186	169
20.25	51.44	72.10	22.73	180	355	169	349	114	319	3.88	32.71	195	178
24.25	61.60	87.60	27.62	189	360	177	354	117	320	3.78	35.78	205	189
Run 102: Increasing heat flux, converging flow area; mass flow rate, 1500 lb/hr (0.189 kg/sec); power to test section, 21 000 W; test section voltage, 26.6 V; inlet bulk temperature, 104 ^oF (313 ^oK); outlet bulk temperature, 152 ^oF (340 ^oK)													
0.25	0.64	24.72×10^3	7.79×10^3	121	323	116	320	104	313	4.30	17.33×10^3	393	112
.50	1.27	24.72	7.79	121	323	116	320	104	313	4.30	17.37	392	112
.75	1.91	24.80	7.82	124	324	119	322	104	313	4.30	17.40	314	112
1.00	2.54	25.22	7.95	127	326	122	323	105	314	4.25	17.69	280	113
1.50	3.81	25.88	8.16	130	328	125	325	105	314	4.25	17.77	243	114
2.00	5.08	27.90	8.80	134	330	128	327	105	314	4.25	17.86	227	114
4.25	10.80	29.10	9.17	141	334	135	330	106	314	4.20	19.14	183	120
8.25	20.96	34.30	10.81	157	343	150	339	107	315	4.15	19.63	139	122
12.25	31.12	41.60	13.11	165	347	157	343	109	316	4.01	20.99	144	127
16.25	41.28	48.60	15.32	173	352	165	347	111	317	3.99	22.65	142	135
20.25	51.44	59.10	18.63	181	356	172	351	113	318	3.91	24.19	150	140
24.25	61.60	71.90	22.67	191	362	181	356	116	320	3.80	26.44	156	148

TABLE I. - Continued. EXPERIMENTAL DATA FOR TAPERED-FLOW-AREA, NONUNIFORM-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	Btu/(ft^2)(hr)	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 103: Increasing heat flux, converging flow area; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 14 580 W; test section voltage, 22.4 V; inlet bulk temperature, 104 ^oF (313 ^oK); outlet bulk temperature, 153 ^oF (340 ^oK)													
0.25	0.64	16.80×10^3	5.30×10^3	116	320	112	318	104	313	4.30	11.56×10^3	400	81
.50	1.27	16.82	5.30	117	320	113	318	104	313	4.30	11.58	355	81
.75	1.91	16.81	5.30	119	322	115	319	105	314	4.25	11.77	318	82
1.00	2.54	17.13	5.40	123	324	119	322	105	314	4.25	11.78	231	82
1.50	3.81	17.56	5.54	126	325	122	323	105	314	4.25	11.84	194	83
2.00	5.08	18.00	5.67	130	328	126	325	105	314	4.25	11.91	160	85
4.25	10.80	19.74	6.22	138	332	134	330	106	314	4.20	12.36	129	88
8.25	20.96	23.30	7.35	154	341	149	338	107	315	4.15	13.08	97	92
12.25	31.12	28.30	8.92	165	347	160	344	109	316	4.01	13.99	92	97
16.25	41.28	33.10	10.44	175	353	169	349	111	317	3.99	15.11	90	102
20.25	51.44	40.30	12.71	183	357	177	354	113	318	3.91	16.13	94	107
24.25	61.60	48.90	15.42	194	363	187	359	116	320	3.80	17.63	97	113
Run 104: Decreasing heat flux, diverging flow area; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 7080 W; test section, 15.4 V; inlet bulk temperature, 118 ^oF (321 ^oK); outlet bulk temperature, 164 ^oF (346 ^oK)													
0.25	0.64	138.40×10^3	43.63×10^3	180	355	171	350	119	322	3.70	14.67×10^3	230	92
.50	1.27	137.10	43.22	191	362	182	357	119	322	3.73	14.59	189	92
.75	1.91	135.00	42.56	199	366	190	361	120	322	3.65	14.74	168	91
1.00	2.54	133.00	41.93	207	370	198	365	120	322	3.65	14.64	149	91
1.50	3.81	----------	---------	---	---	---	---	---	---	----	---------	---	---
2.00	5.08	124.50	39.25	227	382	218	377	122	323	3.60	14.65	116	90
4.00	10.16	106.80	33.67	233	385	225	380	126	325	3.45	14.63	100	89
8.00	20.32	77.60	24.46	233	385	226	381	133	329	3.22	14.18	84	84
12.00	30.48	59.40	18.73	225	380	219	377	139	333	3.05	13.72	79	80
16.00	40.64	46.30	14.60	219	377	214	374	144	335	2.91	13.53	75	76
20.00	50.80	36.30	11.44	213	374	208	371	147	337	2.83	13.03	72	73
24.00	60.96	29.94	9.44	208	371	204	369	150	339	2.76	12.52	71	70

TABLE I. - Concluded. EXPERIMENTAL DATA FOR TAPERED-FLOW AREA,

NONUNIFORM-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	Btu/(ft^2)(hr)	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 105: Decreasing heat flux, diverging flow area; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 13 620 W; test section voltage, 21.1 V; inlet bulk temperature, 109 ^oF (316 ^oK); outlet bulk temperature, 155 ^oF (341 ^oK)													
0.25	0.64	274.70×10^3	86.60×10^3	195	364	177	354	110	317	4.04	27.10×10^3	358	156
.50	1.27	271.00	85.43	201	367	183	357	110	317	4.04	26.98	326	156
.75	1.91	268.00	84.49	214	374	196	364	111	317	3.99	27.03	278	155
1.00	2.54	263.90	83.19	220	378	202	368	111	317	3.99	26.85	257	154
1.50	3.81	256.10	80.74	233	385	215	375	112	318	3.95	26.78	222	153
2.00	5.08	247.20	77.93	240	387	222	379	113	318	3.90	26.64	205	152
4.00	10.16	211.10	66.55	240	389	224	380	117	320	3.77	26.88	185	150
8.00	20.32	153.10	48.27	236	387	222	379	124	324	3.51	26.36	157	143
12.00	30.48	116.50	36.73	226	381	214	374	130	328	3.32	25.66	150	136
16.00	40.64	91.20	28.75	220	378	210	372	135	330	3.18	25.00	140	131
20.00	50.80	71.65	22.59	212	373	203	368	138	332	3.10	24.01	135	125
24.00	60.96	58.65	18.49	202	368	194	363	141	334	3.00	23.21	142	120
Run 106: Decreasing heat flux, diverging flow area; mass flow rate, 1500 lb/hr (0.189 kg/sec); power to test section, 21 300 W; test section voltage, 26.6 V; inlet bulk temperature, 106 ^oF (314 ^oK); outlet bulk temperature, 154 ^oF (341 ^oK)													
0.25	0.64	428.00×10^3	134.93×10^3	213	374	184	358	107	315	4.15	38.82×10^3	487	210
.50	1.27	423.00	133.35	221	378	192	362	107	315	4.15	38.61	438	210
.75	1.91	418.40	131.90	237	387	208	371	108	315	4.11	39.22	370	211
1.00	2.54	412.20	129.95	244	391	215	375	108	315	4.11	38.95	342	210
1.50	3.81	399.00	125.79	256	398	227	382	110	317	4.03	39.35	305	211
2.00	5.08	385.20	121.43	262	401	234	385	111	317	3.99	39.42	284	210
4.00	10.16	329.20	103.78	261	400	236	387	115	319	3.83	39.18	255	207
8.00	20.32	238.70	75.25	258	399	237	387	122	323	3.59	38.95	210	197
12.00	30.48	182.10	57.41	244	391	226	381	128	327	3.38	37.88	201	188
16.00	40.64	141.90	44.73	237	387	221	378	134	330	3.20	37.15	188	180
20.00	50.80	111.20	35.06	225	380	211	373	137	332	3.10	35.72	184	172
24.00	60.96	91.15	28.74	217	376	205	369	139	333	3.05	34.22	179	165
Run 107: Decreasing heat flux, diverging flow area; mass flow rate, 2000 lb/hr (0.252 kg/sec); power to test section, 30 800 W; test section voltage, 31.4 V; inlet bulk temperature, 101 ^oF (311 ^oK); outlet bulk temperature, 149 ^oF (338 ^oK)													
0.25	0.64	649.00×10^3	204.60×10^3	230	383	186	359	102	312	4.40	49.50×10^3	681	263
.50	1.27	643.00	202.71	244	391	200	367	'02	312	4.40	49.25	581	262
.75	1.91	635.50	200.34	256	398	212	373	103	313	4.35	49.30	518	261
1.00	2.54	625.50	197.19	266	403	222	379	103	313	4.35	49.00	470	260
1.50	3.81	608.50	191.83	278	410	235	386	105	314	4.75	49.44	422	258
2.00	5.08	586.00	184.74	285	414	243	390	106	314	4.20	49.45	390	257
4.00	10.16	500.50	157.78	283	413	245	392	110	317	4.03	50.05	350	255
8.00	20.32	362.00	114.12	275	408	243	390	117	320	3.77	50.00	292	247
12.00	30.48	275.50	86.85	263	402	235	386	123	324	3.55	48.53	267	234
16.00	40.64	214.00	67.46	257	398	227	382	129	327	3.35	47.51	253	225
20.00	50.80	168.10	52.99	240	389	219	377	132	329	3.25	45.62	238	214
24.00	60.96	137.80	43.44	230	383	212	373	134	330	3.20	43.69	230	205

TABLE II. - EXPERIMENTAL DATA FOR CONSTANT-FLOW-AREA, TAPERED-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	$Btu/(ft^2)(hr)$	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 1: Decreasing heat flux in the direction of flow; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 15 650 W; test section voltage, 30.6 V; inlet bulk temperature, 101 ^oF (312 ^oK); outlet bulk temperature, 151.5 ^oF (340 ^oK)													
0.25	0.64	198.5×10^3	62.6×10^3	176	353	156	342	101	311	4.47	21.49×10^3	355	136
.50	1.27	197.1	62.1	184	358	165	347	102	312	4.40	22.02	308	138
.75	1.91	---------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	194.3	61.3	201	367	182	356	103	313	4.35	22.30	242	138
1.50	3.81	192.1	60.6	214	374	195	364	104	313	4.30	22.58	207	139
2.00	5.08	189.3	59.7	223	379	204	369	104	313	4.30	22.58	186	139
3.94	10.00	181.0	57.1	237	387	219	377	108	315	4.12	23.63	159	141
6.94	17.62	167.8	52.9	237	387	219	377	112	318	3.95	24.62	152	143
9.94	25.24	156.8	49.4	234	385	216	375	117	320	3.78	25.88	153	146
12.94	32.86	147.3	46.4	234	385	215	375	121	323	3.61	26.86	151	147
15.94	40.48	138.8	43.8	236	386	217	376	125	325	3.49	27.91	144	149
18.94	48.10	131.0	41.3	226	381	207	370	128	326	3.40	28.59	158	150
21.94	55.72	124.2	39.2	228	382	210	372	132	329	3.25	29.54	151	151
Run 2: Decreasing heat flux in the direction of flow; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 16 390 W; test section voltage, 30.0 V; inlet bulk temperature, 149 ^oF (338 ^oK); outlet bulk temperature, 200.5 ^oF (367 ^oK)													
0.25	0.64	203.5×10^3	64.2×10^3	217	376	198	365	149	338	2.80	34.09×10^3	388	158
.50	1.27	202.2	63.7	223	379	205	369	150	339	2.78	34.42	343	158
.75	1.91	---------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	199.3	62.8	237	387	219	377	151	339	2.72	34.75	274	158
1.50	3.81	197.1	62.1	248	393	230	383	151	339	2.72	34.75	233	158
2.00	5.08	194.1	61.2	256	398	238	388	152	340	2.70	35.10	211	159
3.94	10.00	185.6	58.5	267	404	249	394	155	341	2.64	35.81	184	160
6.94	17.62	172.0	54.2	267	404	249	394	160	344	2.51	37.32	179	161
9.94	25.24	160.8	50.7	267	404	249	394	164	346	2.43	38.12	175	161
12.94	32.86	151.0	47.6	270	405	252	394	169	349	2.33	39.39	168	162
15.94	40.48	142.4	44.9	271	406	253	396	173	351	2.27	40.28	164	163
18.94	48.10	134.4	42.4	265	403	247	393	177	354	2.20	41.71	177	166
21.94	55.72	127.4	40.2	267	404	249	394	180	355	2.14	42.20	170	165
Run 3: Decreasing heat flux in the direction of flow; mass flow rate, 754 lb/hr (0.095 kg/sec); power to test section, 12 240 W; test section voltage, 26.6 V; inlet bulk temperature, 149 ^oF (338 ^oK); outlet bulk temperature, 200 ^oF (366 ^oK)													
0.25	0.64	150.0×10^3	47.3×10^3	207	370	193	363	150	339	2.78	26.10×10^3	326	127
.50	1.27	149.0	47.0	213	374	199	366	150	339	2.78	26.10	284	127
.75	1.91	---------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	146.9	46.3	226	381	212	373	151	339	2.72	26.35	225	127
1.50	3.81	145.3	45.8	234	385	220	378	152	340	2.70	26.61	199	127
2.00	5.08	143.0	45.1	237	387	223	379	152	340	2.70	26.61	188	127
3.94	10.00	136.9	43.2	253	396	239	388	155	341	2.63	26.88	152	126
6.94	17.62	126.8	40.0	257	398	243	390	160	344	2.51	28.30	142	129
9.94	25.24	118.5	37.4	256	398	242	390	164	346	2.43	28.90	141	130
12.94	32.86	111.3	35.1	256	398	243	390	168	349	2.35	29.87	137	130
15.94	40.48	104.9	33.1	259	399	246	392	172	351	2.29	30.55	131	131
18.94	48.10	99.0	31.2	254	396	241	389	176	353	2.20	31.62	140	133
21.94	55.72	93.9	29.6	257	398	244	390	180	355	2.15	32.00	135	132

TABLE II. - Continued. EXPERIMENTAL DATA FOR CONSTANT-FLOW-AREA,

TAPERED-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	$Btu/(ft^2)(hr)$	W/m^2	^{o}F	^{o}K	^{o}F	^{o}K	^{o}F	^{o}K				
Run 4: Decreasing heat flux in the direction of flow; mass flow rate, 744 lb/hr (0.094 kg/sec); power to test section, 11 700 W; test section voltage, 26.1 V; inlet bulk temperature, 102 ^{o}F (312 ^{o}K); outlet bulk temperature, 152 ^{o}F (340 ^{o}K)													
0.25	0.64	144.5×10^3	45.6×10^3	166	348	152	340	103	313	4.35	16.59×10^3	290	109
.50	1.27	143.5	45.2	173	351	159	344	103	313	4.35	16.59	252	109
.75	1.91	---------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	141.7	44.7	188	360	174	352	104	313	4.30	16.80	199	110
1.50	3.81	140.0	44.1	202	368	188	360	104	313	4.30	16.80	164	110
2.00	5.08	137.8	43.4	209	371	195	364	105	314	4.25	16.91	150	110
3.94	10.00	131.8	41.5	226	381	213	374	108	315	4.12	17.58	123	111
6.94	17.62	122.1	38.5	226	381	213	374	113	318	3.90	18.58	118	113
9.94	25.24	114.1	36.0	222	379	209	371	117	320	3.78	19.26	120	115
12.94	32.86	107.2	33.8	223	379	210	372	121	323	3.61	19.99	116	116
15.94	40.48	101.0	31.8	223	379	210	372	125	325	3.49	20.77	114	118
18.94	48.10	95.3	30.3	215	375	202	368	129	327	3.34	21.62	124	119
21.94	55.72	90.4	28.5	218	376	206	370	132	329	3.25	21.98	116	119
Run 5: Decreasing heat flux in the direction of flow; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 7940 W; test section voltage, 20.75 V; inlet bulk temperature, 103 ^{o}F (313 ^{o}K); outlet bulk temperature, 149 ^{o}F (338 ^{o}K)													
0.25	0.64	91.1×10^3	28.7×10^3	154	341	146	336	104	313	4.30	11.29×10^3	213	85
.50	1.27	90.5	28.5	158	343	150	339	104	313	4.30	11.29	193	85
.75	1.91	---------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	89.2	28.1	175	353	167	348	105	314	4.25	11.37	141	80
1.50	3.81	88.2	27.8	184	358	175	353	105	314	4.25	11.37	124	80
2.00	5.08	86.8	27.4	193	363	184	358	106	314	4.20	11.51	109	80
3.94	10.00	83.3	26.3	211	373	202	368	109	316	4.08	11.90	87	81
6.94	17.62	77.0	24.3	216	375	207	370	113	318	3.91	12.49	79	83
9.94	25.24	72.0	22.7	213	374	205	369	117	320	3.77	12.94	79	84
12.94	32.86	67.6	21.3	212	373	204	369	121	323	3.61	13.53	78	85
15.94	40.48	63.7	20.1	212	373	204	369	124	324	3.50	13.85	76	85
18.94	48.10	60.1	18.9	205	369	197	365	128	326	3.39	14.30	83	86
21.94	55.72	57.0	18.0	207	370	199	366	131	328	3.29	14.78	79	87
Run 6: Decreasing heat flux in the direction of flow; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 8280 W; test section voltage, 21.9 V; inlet bulk temperature, 149 ^{o}F (338 ^{o}K); outlet bulk temperature, 199.5 ^{o}F (366 ^{o}K)													
0.25	0.64	92.5×10^3	29.2×10^3	198	365	189	360	150	339	2.78	17.21×10^3	222	91
.50	1.27	91.8	28.9	202	368	193	363	150	339	2.78	17.21	199	91
.75	1.91	91.2	28.8	211	373	202	368	150	339	2.78	17.21	164	91
1.00	2.54	90.5	28.5	217	376	208	371	151	339	2.72	17.38	148	91
1.50	3.81	89.6	28.2	228	382	219	377	152	340	2.70	17.55	125	91
2.00	5.08	88.2	27.8	235	386	226	381	155	341	2.63	17.73	116	91
3.94	10.00	84.4	26.6	248	393	239	388	160	344	2.51	18.66	99	93
6.94	17.62	78.2	24.7	251	395	242	390	164	346	2.43	19.06	93	93
9.94	25.24	73.0	23.0	252	395	243	390	168	349	2.35	19.70	90	93
12.94	32.86	68.6	21.6	252	395	244	391	172	351	2.29	20.15	88	95
15.94	40.48	64.7	20.4	254	396	246	392	176	353	2.20	20.86	85	95
18.94	48.10	61.0	19.2	246	392	238	388	180	355	2.15	21.11	97	95
21.94	55.72	57.9	18.3	252	395	246	392	183	357	2.10	21.62	83	96

TABLE II - Continued. EXPERIMENTAL DATA FOR CONSTANT-FLOW-AREA,

TAPERED-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	$Btu/(ft^2)(hr)$	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 7: Decreasing heat flux in the direction of flow; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 8280 W; test section voltage, 21.95 V; inlet bulk temperature, 200.5 ^oF (367 ^oK); outlet bulk temperature, 252 ^oF (395 ^oK)													
0.25	0.64	92.9×10^3	29.3×10^3	245	391	236	386	201	367	1.87	24.42×10^3	242	100
.50	1.27	92.2	29.1	250	394	242	390	202	368	1.86	24.56	210	100
.75	1.91	91.6	28.9	258	299	250	394	202	368	1.86	24.56	174	100
1.00	2.54	90.9	28.7	263	401	255	397	203	368	1.85	24.71	159	100
1.50	3.81	89.9	28.3	271	406	263	401	203	368	1.85	24.71	137	100
2.00	5.08	88.6	27.9	279	410	271	406	204	369	1.84	24.85	120	100
3.94	10.00	84.7	26.7	289	416	281	411	207	370	1.80	25.33	104	101
6.94	17.62	78.5	24.7	293	418	285	414	212	373	1.75	26.09	98	102
9.94	25.24	73.3	23.1	291	417	283	413	216	375	1.71	26.68	99	103
12.94	32.86	68.9	21.7	295	419	287	415	221	378	1.67	27.45	95	104
15.94	40.48	64.9	20.5	298	421	290	416	225	380	1.63	28.10	91	105
18.94	48.10	61.3	19.3	293	418	285	414	229	383	1.60	28.71	99	106
21.94	55.72	58.2	18.3	296	420	288	415	232	384	1.57	29.19	94	106
Run 8: Decreasing heat flux in the direction of flow; mass flow rate, 373 lb/hr (0.047 kg/sec); power to test section, 5880 W; test section voltage, 18.3 V; inlet bulk temperature, 101 ^oF (311 ^oK); outlet bulk temperature, 150 ^oF (339 ^oK)													
0.25	0.64	71.0×10^3	22.4×10^3	150	339	143	335	102	312	4.40	8.21×10^3	170	62
.50	1.27	70.5	22.2	155	341	148	338	102	312	4.40	8.21	151	62
.75	1.91	--------	--------	---	---	---	---	---	---	----	---------	---	---
1.00	2.54	69.5	21.9	169	349	162	345	103	313	4.35	8.31	116	63
1.50	3.81	68.8	21.7	179	355	172	351	103	313	4.35	8.31	98	63
2.00	5.08	67.7	21.3	188	360	181	356	104	313	4.30	8.42	86	63
3.94	10.00	64.8	20.4	208	371	201	367	107	315	4.17	8.69	67	64
6.94	17.62	60.0	18.9	215	375	209	371	111	317	3.99	9.12	59	65
9.94	25.24	56.1	17.7	216	375	209	371	116	320	3.80	9.51	58	66
12.94	32.86	52.7	16.6	216	375	209	371	120	322	3.66	9.94	57	67
15.94	40.48	49.6	15.6	214	374	208	371	124	324	3.51	10.33	57	68
18.94	48.10	46.9	14.8	206	370	200	366	127	326	3.41	10.58	61	69
21.94	55.72	44.5	14.0	207	370	201	367	131	328	3.29	11.02	60	69
Run 9: Decreasing heat flux in the direction of flow; mass flow rate, 373 lb/hr (0.047 kg/sec); power to test section, 5940 W; test section voltage, 18.4 V; inlet bulk temperature, 149.5 ^oF (338 ^oK); outlet bulk temperature, 199.5 ^oF (366 ^oK)													
0.25	0.635	71.8×10^3	22.6×10^3	192	362	184	358	150	339	2.78	12.8×10^3	197	72
.50	1.270	71.3	22.5	196	364	188	360	150	339	2.78	12.8	175	72
.75	1.905	70.8	22.3	202	368	194	363	151	339	2.72	13.0	154	72
1.00	2.54	70.2	22.1	209	371	201	367	151	339	2.72	13.0	131	72
1.50	3.81	69.5	21.9	220	378	212	373	152	340	2.70	13.1	108	72
2.00	5.08	68.4	21.6	227	381	219	377	153	340	2.69	13.2	97	72
3.935	10.00	65.4	20.6	240	389	233	385	156	342	2.60	13.4	79	72
6.00	17.62	60.6	19.1	244	391	237	387	161	345	2.50	13.9	74	73
9.00	25.24	57.0	18.0	243	390	236	386	164	346	2.43	14.2	73	73
12.00	32.86	53.2	16.8	244	391	237	387	169	349	2.33	14.7	72	74
15.00	40.48	50.2	15.8	245	391	238	388	173	351	2.28	15.0	71	74
18.00	48.10	47.4	14.9	241	389	234	385	176	353	2.20	15.6	75	75
21.00	55.72	44.9	14.2	244	391	237	387	180	355	2.15	15.8	72	75

TABLE II. - Continued. EXPERIMENTAL DATA FOR CONSTANT-FLOW-AREA,

TAPERED-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, q		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	Btu/(ft^2)(hr)	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 10: Decreasing heat flux in the direction of flow; mass flow rate, 371 lb/hr (0.047 kg/sec); power to test section, 5940 W; test section voltage, 18.5 V; inlet bulk temperature, 198.3 ^oF (366 ^oK); outlet bulk temperature, 249 ^oF (394 ^oK)													
0.25	0.635	72.6×10^3	22.9×10^3	237	387	230	383	199	366	1.90	17.8×10^3	214	78
.50	1.270	72.2	22.7	243	390	236	386	199	366	1.90	17.8	178	78
.75	1.905	71.6	22.6	249	394	242	390	200	366	1.89	18.0	155	79
1.00	2.54	71.0	22.4	254	396	247	393	200	366	1.89	18.0	138	79
1.50	3.81	70.3	22.2	262	401	255	397	201	367	1.87	18.1	119	79
2.00	5.08	69.2	21.8	267	404	260	400	202	368	1.86	18.2	109	79
3.935	10.00	66.2	20.9	279	410	272	406	205	369	1.82	18.6	90.0	79
6.00	17.62	61.3	19.3	282	412	275	408	209	371	1.78	19.0	85	80
9.00	25.24	57.3	18.1	284	413	277	409	213	374	1.74	19.5	81	81
12.00	32.86	53.9	17.0	283	413	276	409	218	376	1.70	20.1	84	81
15.00	40.48	50.8	16.0	284	413	277	409	222	379	1.66	20.5	84	82
18.00	48.10	47.9	15.1	284	413	277	409	225	380	1.63	20.8	81	83
21.00	55.72	45.4	14.3	287	415	280	411	229	383	1.60	21.3	82	83
Run 11: Increasing heat flux in the direction of flow; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 15 840 W; test section voltage, 30.5 V; inlet bulk temperature, 102 ^oF (312 ^oK); outlet bulk temperature, 152 ^oF (340 ^oK)													
0.25	0.635	90.3×10^3	28.5×10^3	146	336	128	326	102	312	4.40	22.0×10^3	342	137
.50	1.270	90.7	28.6	153	340	135	330	102	312	4.40	22.0	270	137
.75	1.905	91.4	28.8	157	343	139	333	103	313	4.35	22.3	249	138
1.50	3.81	92.4	29.1	169	349	151	339	103	313	4.35	22.3	189	138
2.00	5.08	92.8	29.3	176	353	158	343	104	313	4.30	22.6	169	139
4.00	10.16	95.6	30.1	186	359	167	348	104	313	4.30	22 6	149	139
8.00	20.32	101.4	31.2	195	364	178	354	109	316	4.08	23.8	143	141
12.00	30.48	106.9	33.7	197	365	180	355	112	318	3.95	24.6	153	143
16.00	40.64	114.4	36.1	209	371	192	362	116	320	3.80	25.5	145	144
20.00	50.80	121.8	38.4	216	375	198	365	121	323	3.61	26.9	152	147
Run 12: Increasing heat flux in the direction of flow; mass flow rate, 1000 lb/hr (0.126 kg/sec); power to test section, 16 080 W; test section voltage, 30.8; inlet bulk temperature, 150 ^oF (339 ^oK); outlet bulk temperature, 200 ^oF (366 ^oK)													
0.25	0.635	92.3×10^3	29.1×10^3	193	363	175	353	150	339	2.78	34.4×10^3	345	158
.50	1.270	92.6	29.2	197	365	179	355	150	339	2.78	34.4	298	158
.75	1.950	93.3	29.4	201	367	183	357	151	339	2.72	34.8	272	158
1.50	3.81	94.3	29.7	210	372	192	362	151	339	2.72	34.8	215	158
2.00	5.08	94.8	29.9	216	375	198	365	152	340	2.70	35.1	192	159
4.00	10.16	97.7	30.8	223	379	205	369	152	340	2.70	35.1	172	159
8.00	20.32	103.5	32.6	233	385	215	375	157	343	2.58	36.4	166	160
12.00	30.48	109.2	34.4	236	386	218	376	160	344	2.51	37.3	175	161
16.00	40.64	116.9	36.8	248	393	231	384	164	346	2.43	38.1	162	161
20.00	50.80	124.4	39.2	252	395	234	385	169	349	2.33	39.4	177	162

TABLE II - Concluded. EXPERIMENTAL DATA FOR CONSTANT-FLOW-AREA,

TAPERED-HEAT-FLUX TEST SECTION

Distance from start of heating, x		Heat flux, x		Local outside wall temperature, T_o		Local inside wall temperature, T_i		Local bulk temperature, T_B		Local Prandtl number, Pr	Local Reynolds number, Re	Local Nusselt number, Nu	Local fully developed Nusselt number, Nu_{fd}
in.	cm	$Btu/(ft^2)(hr)$	W/m^2	^oF	^oK	^oF	^oK	^oF	^oK				
Run 13: Increasing heat flux in the direction of flow; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 8280 W; test section voltage, 21.9 V; inlet bulk temperature, 102 ^oF (312 ^oK); outlet bulk temperature, 152 ^oF (340 ^oK)													
0.25	0.635	46.6×10^3	14.7×10^3	134	330	126	325	102	312	4.40	11.0×10^3	191	79
.50	1.270	46.8	14.8	138	332	130	328	102	312	4.40	11.0	164	79
.75	1.905	47.1	14.9	142	334	134	330	103	313	4.35	11.1	149	79
1.50	3.81	47.6	15.0	153	340	145	336	103	313	4.35	11.1	111	79
2.00	5.08	47.9	15.1	161	345	153	340	104	313	4.30	11.3	96	80
4.00	10.16	49.3	15.5	173	351	165	347	104	313	4.30	11.3	79	80
8.00	20.32	52.3	16.5	184	358	176	353	109	316	4.08	11.9	76	81
12.00	30.48	55.2	17.4	186	359	178	354	112	318	3.95	12.3	81	82
16.00	40.64	59.0	18.6	197	365	189	360	116	320	3.80	12.8	78	83
20.00	50.80	62.8	19.8	203	368	195	364	121	323	3.61	13.4	82	84
Run 14: Increasing heat flux in the direction of flow; mass flow rate, 500 lb/hr (0.063 kg/sec); power to test section, 8280 W; test section voltage, 22.0 V; inlet bulk temperature, 151 ^oF (339 ^oK); outlet bulk temperature, 201.5 ^oF (369 ^oK)													
0.25	0.635	47.1×10^3	14.8×10^3	179	355	171	350	151	339	2.72	17.4×10^3	220	91
.50	1.270	47.3	14.9	182	356	174	352	151	339	2.72	17.4	192	91
.75	1.905	47.6	15.0	185	358	177	354	152	340	2.70	17.6	178	91
1.50	3.81	48.1	15.2	195	364	187	359	152	340	2.70	17.6	128	91
2.00	5.08	48.4	15.3	201	367	193	363	153	340	2.69	17.7	113	92
4.00	10.16	49.7	15.7	209	371	201	367	153	340	2.69	17.7	97	92
8.00	20.32	52.8	16.7	220	378	212	373	158	343	2.56	18.3	91	92
12.00	30.48	55.8	17.6	225	380	217	376	161	345	2.50	18.7	92	92
16.00	40.64	59.6	18.8	236	386	228	382	165	347	2.41	19.3	88	93
20.00	50.80	63.5	20.0	240	389	232	384	170	350	2.32	19.9	95	94

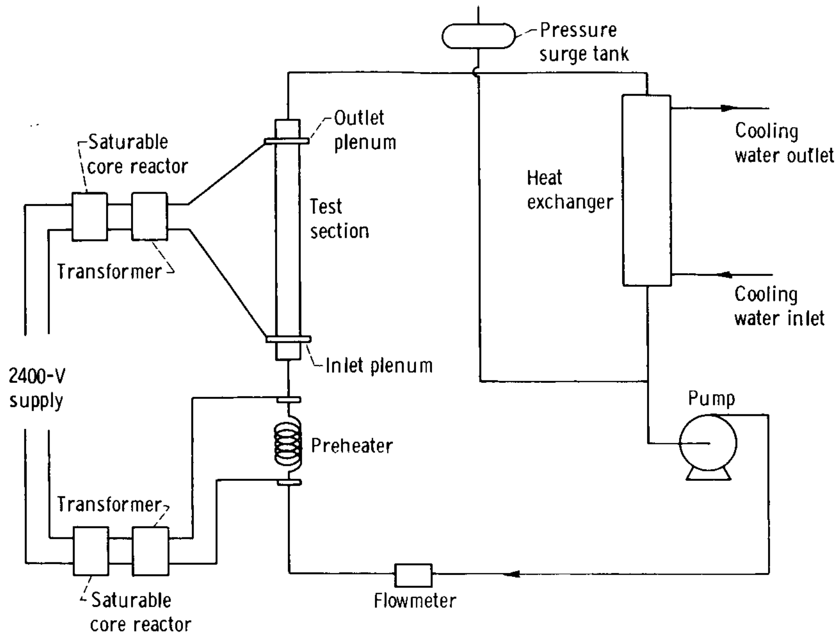


Figure 1. - System flow diagram.

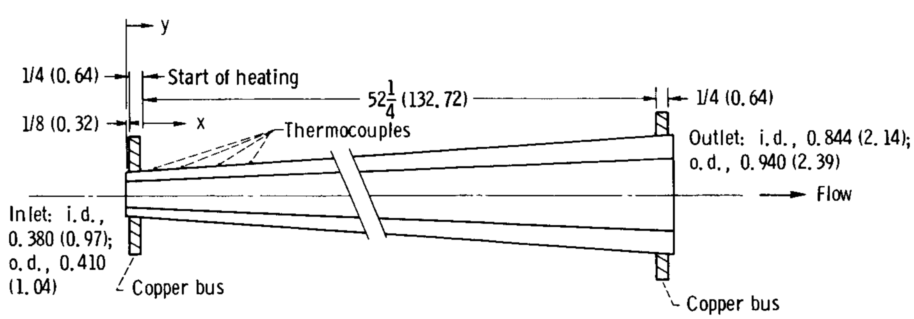


Figure 2. - Tapered tube test section. Flow can be reversed, so that inlet becomes outlet. Dimensions are in inches (cm).

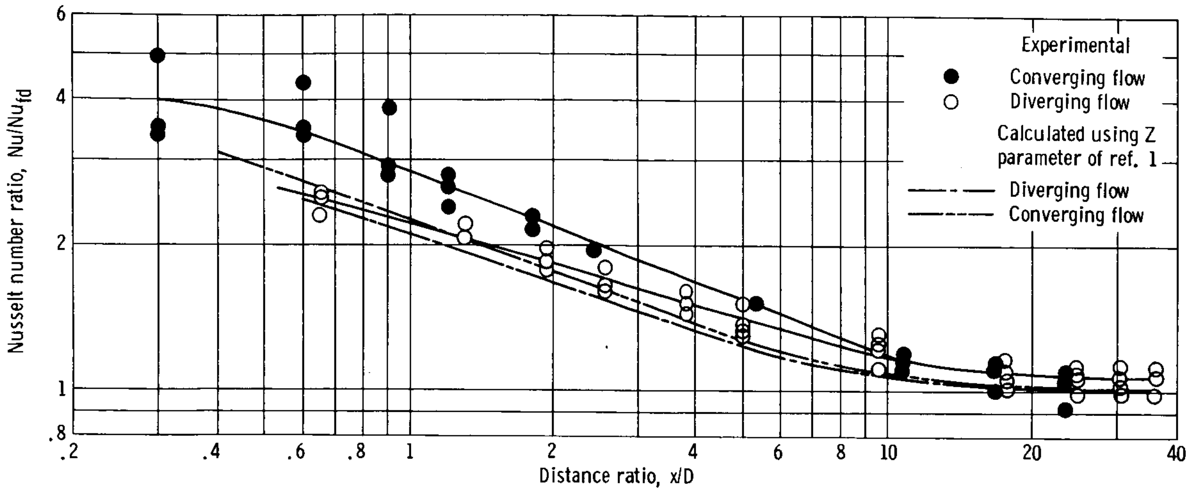
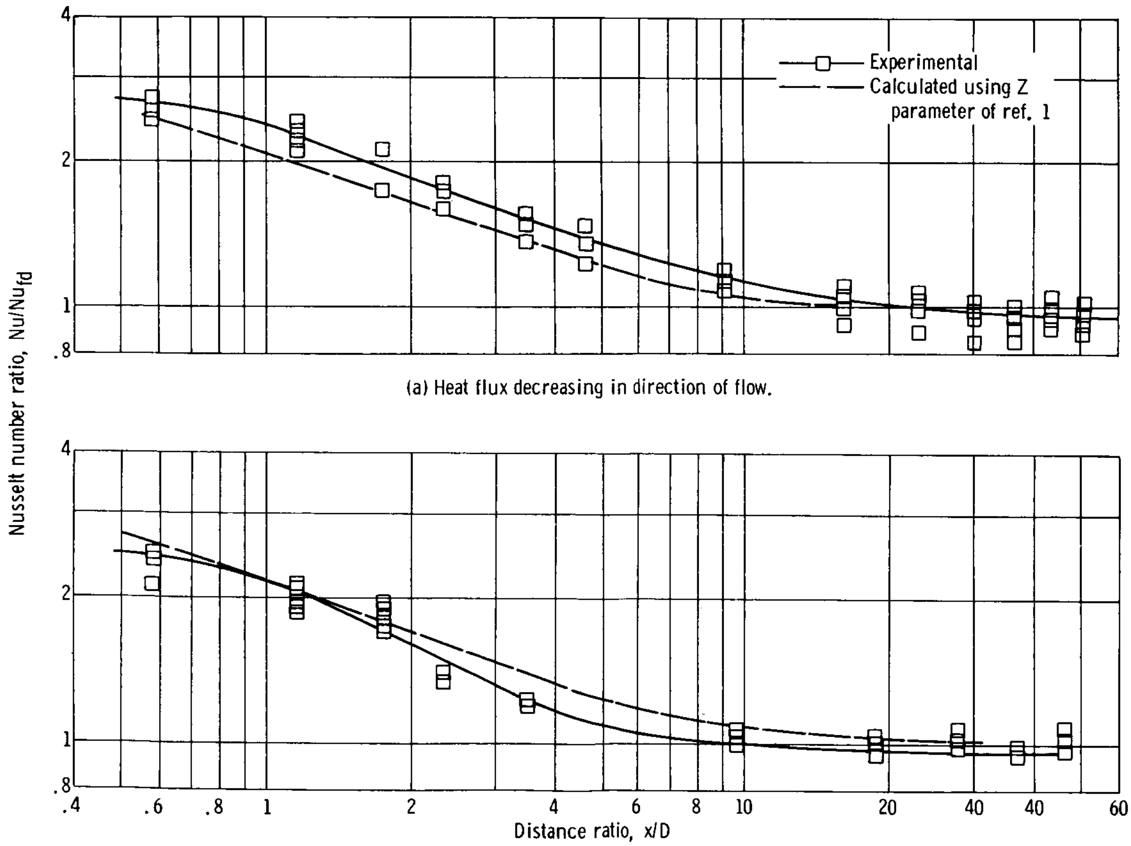


Figure 3. - Variation in Nusselt number ratio with length to local diameter ratio from start of heating for tapered-cross-sectional flow-area test section.



(a) Heat flux decreasing in direction of flow.

(b) Heat flux increasing in direction of flow.

Figure 4. - Variation in Nusselt number ratio with length to local diameter ratio from start of heating for constant-flow-area test section.

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—National Aeronautics and Space Act of 1958

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